Polarized Heavy Quarkonium Production in the Color Evaporation Model

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Overview

1. Introduction

2. Results at Parton Level

3. Results at Hadron Level
   - Energy Dependence
   - Rapidity Dependence

4. Conclusion and Future
Quarkonium Polarization Problem

- The mechanism of producing Quarkonium has not been solved
- Non Relativistic QCD (NRQCD), a common method to predict quarkonium production, has difficulties describing production and polarization simultaneously
- No polarization prediction has been made using the Color Evaporation Model (CEM) until now (submitted)
Non Relativistic QCD (NRQCD)

- e.g. for $J/\psi$, $\sigma_{J/\psi} = \sum_n \sigma_{cc}[n] \langle O_{J/\psi}[n] \rangle$
- $\sigma_{cc}[n]$ are cross sections in a particular color and spin state $n$ calculated by perturbative QCD
- $\langle O_{J/\psi}[n] \rangle$ are nonperturbative Long Distance Matrix Elements (LDMEs) that describe the conversion of $cc[n]$ state into final state $J/\psi$, assuming that the hadronization does not change the spin or momentum
- LDMEs are assumed to be universal and are expanded in powers of $v/c$
- leading term is $n = 3S^1_1$, corresponds to the color singlet model
- color octet states are subleading terms $1S^8_0$, $3S^8_1$, and $3P^8_J$
- mixing of LDMEs are determined by fitting to data, usually $p_T$ distributions above some $p_T$ cut
NRQCD LDMEs\textsuperscript{1} depend on $p_T$ cut/experiment

\textbf{Included in fits}

\begin{itemize}
  \item $e^+e^-$
  \item $e p$
  \item $p p$
\end{itemize}

\begin{itemize}
  \item Butenschon & Kniehl \textup{p}_T > 3 \text{ GeV}
  \item Gong et al. \textup{p}_T > 5 \text{ GeV}
  \item Chao et al. \textup{p}_T > 7 \text{ GeV}
\end{itemize}

\textsuperscript{1}N. Brambilla et al., Eur. Phys. J. C 74, 2981 (2014)
## Color Evaporation Model

- All Quarkonium states are treated like $Q\bar{Q}$ ($Q = c, b$) below $HH$ ($H = D, B$) threshold.
- Does not separate states into color or spin.
- Color is said to be ‘evaporated’ away during transition from pair to Quarkonium state while preserving the kinematics.
- Mostly calculated by perturbative QCD.
- Fewer parameters than NRQCD (one $F_Q$ for each Quarkonium state).
- $F_Q$ is fixed by comparison of NLO calculation of $\sigma_Q^{CEM}$ to $\sqrt{s}$ for $J/\psi$ and $\Upsilon$, $\sigma(x_F > 0)$ and $Bd\sigma/dy|_{y=0}$ for $J/\psi$, $Bd\sigma/dy|_{y=0}$ for $\Upsilon$.
- Spin has been averaged over, no previous prediction of polarization in CEM.
Color Evaporation Model

Leading Order Total Cross Section

\[ \sigma = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}) \delta(\hat{s} - x_1 x_2 s), \]

\( F_Q \) is a universal factor for the quarkonium state and is independent of the projectile, target, and energy.

Leading Order Rapidity Distribution

\[ \frac{d\sigma}{dy} = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \frac{d\hat{s}}{s} f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}), \]

where \( x_{1,2} = (\sqrt{\hat{s}/s}) \exp(\pm y) \).

We take the factorization and renormalization scales to be \( \mu^2 = \hat{s} \).
Polarization of Quarkonium

- defined as the tendency of quarkonium to be in a certain total angular momentum state
- e.g. an unpolarized $J = 1$ production means yielding $J_z = -1, 0, +1$ equally
- longitudinal $\rightarrow$ peak at $\vartheta = \pi/2$
- transverse $\rightarrow$ peaks at $\vartheta = 0, \pi$
Defining Polarization

Polarization in the Helicity Basis

- helicity is the projection of angular momentum onto the direction of momentum
- if the helicities are the same, then $J_z = 0$ (longitudinal)
- if the helicities are the opposite, then $J_z = \pm 1$ (transverse)
Polarized Partonic Cross Section

The individual partonic cross sections for the longitudinal and transverse polarizations are

\[
\hat{\sigma}_{J_z=0}^{q\bar{q}}(\hat{s}) = \frac{16\pi\alpha_s^2}{27\hat{s}^2} \hat{s}M^2 \chi ,
\]

\[
\hat{\sigma}_{J_z=\pm 1}^{q\bar{q}}(\hat{s}) = \frac{4\pi\alpha_s^2}{27\hat{s}^2} \hat{s} \chi ,
\]

\[
\hat{\sigma}_{J_z=0}^{gg}(\hat{s}) = \frac{\pi\alpha_s^2}{12\hat{s}} \left[ \left( 4 - \frac{31M^2}{\hat{s}} + \frac{33M^2}{\hat{s} - 4M^2} \right) \chi 
+ \left( \frac{4M^4}{\hat{s}^2} + \frac{31M^2}{2\hat{s}} - \frac{33M^2}{2(\hat{s} - 4M^2)} \right) \ln \frac{1 + \chi}{1 - \chi} \right] ,
\]

\[
\hat{\sigma}_{gg}^{J_z=\pm 1}(\hat{s}) = \frac{\pi\alpha_s^2}{24\hat{s}} \left[ -11 \left( 1 + \frac{3M^2}{\hat{s} - 4M^2} \right) \chi 
+ \left( 4 + \frac{M^2}{2\hat{s}} + 33 \frac{M^2}{2(\hat{s} - 4M^2)} \right) \ln \frac{1 + \chi}{1 - \chi} \right] ,
\]

where \( \chi = \sqrt{1 - 4M^2/\hat{s}}. \)
Total Partonic Cross Section

The sum of the results, \( \hat{\sigma}_{ij}^{J_z=0} + \hat{\sigma}_{ij}^{J_z=+1} + \hat{\sigma}_{ij}^{J_z=-1} \), is equal to the total partonic cross section\(^2\)

\[
\hat{\sigma}_{q\bar{q}}^{\text{tot.}}(\hat{s}) = \frac{8\pi \alpha_s^2}{27\hat{s}^2}(\hat{s} + 2M^2)\chi ,
\]

\[
\hat{\sigma}_{gg}^{\text{tot.}}(\hat{s}) = \frac{\pi \alpha_s^2}{3\hat{s}} \left[ - \left( 7 + \frac{31M^2}{\hat{s}} \right) \frac{1}{4}\chi 
+ \left( 1 + \frac{4M^2}{\hat{s}} + \frac{M^4}{\hat{s}^2} \right) \ln \frac{1 + \chi}{1 - \chi} \right] .
\]

- convoluted with the CTEQ6L1 parton distribution functions (PDFs)
- obtain cross section \( \sigma \) as a function of \( \sqrt{s} \) and the rapidity distribution, \( d\sigma/dy \)
- \( \alpha_s = g_s^2/4\pi \) is calculated at one-loop level
- assume that the polarization is unchanged by the transition from the parton level to the hadron level

Behavior within the integration limits

- contribution from gluon fusion process is longitudinal
- contribution from quark annihilation process is transverse
- both fractions decrease as a function of $\hat{s}$
Energy Dependence

- $\psi$ production is more than 50% for $\sqrt{s} > 10$ GeV, and saturates at 80% at high energies
- $\Upsilon$ production is more than 50% for $\sqrt{s} > 50$ GeV, and saturates at 90% at high energies
- $c\bar{c}$ and $b\bar{b}$ production turnover, dominantly transversely polarized at high energies

$^3$V. Cheung & R. Vogt, submitted
Rapidity dependence of longitudinal polarization fraction

Rapidity Dependence

- Fraction is greatest at $y = 0$ and decreases as $|y|$ increases
- Near transverse polarization of $\Upsilon$ at fixed-target energies

\[ \frac{d\sigma^{J=0}_t}{dy} / \frac{d\sigma^{tot}}{dy} \]
Ongoing

Separation of $S = 1, S_z = 0$ (triplet) from $S = 0, S_z = 0$ (singlet)

- sorted by $J_z$ does not distinguish the triplet state from singlet state
- enforce $S = 1$

Extraction of $L = 0$

- enforce $L = 0$ so $S = 1, L = 0 \rightarrow J = 1$
- make sense to calculate the polarization parameter, $\lambda_\theta^{[5]}$ for comparison

Calculation of $\lambda_\theta$

$$\lambda_\theta = \frac{\mathcal{N} - 3|a_0|^2}{\mathcal{N} + |a_0|^2},$$

where $\mathcal{N}$ is the total production amplitude and $|a_0|^2$ is the longitudinal production amplitude.

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Conclusion

- presented the energy and rapidity dependence of the polarization of heavy quarkonium production in $p + p$ collisions
- longitudinal at most energies and around central rapidity
- transverse at the kinematic limits of the calculation where $q\bar{q}$ production is dominant
- enforcing $J = 1$ is still in progress

Future

- leading order calculation → cannot speak to the $p_T$ dependence
- explore the $p_T$ and rapidity dependence of the polarization of a single heavy quark at leading order
- then investigate the high $p_T$ polarization of heavy quark pairs
Backup Slides
from left to right: unpolarized, totally transverse, totally longitudinal.

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